Investigation of the mechanism of Flame Transmission from a Vessel to a Discharge Duct

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1 Introduction

The issue of gas explosions vented through relief pipes is a matter of importance for the security of industrial plants. It has been shown in previous papers that the presence of a duct to discharge the explosion products from a vessel may severely increase the overpressure explosion. The intensification of the combustion in the vessel was proved to be triggered by a secondary explosion in the initial part of the duct.

We had shown that inserting a wire-net at the entrance of the duct is able to prevent the occurrence of the secondary explosion. According to the surface area of the insert, it can quench partially or totally the flame, thus preventing its strong acceleration. The effectiveness of the wire net in decreasing the temperature of the exhaust gases was analyzed by means of a nodal thermal network model [1].

In this work, we investigate in more details the conditions of flame quenching as function of the chamber length and the ratio of chamber volume to discharge surface, in view of using the model for insert scaling.

2 Flame transmission from vessel to duct without insert

2.1 Mechanism of flame transmission at the tube entrance

In previous studies [1], flame transmission has been investigated in a cylindrical plexiglas transparent vessel (reference setup : length $L_V = 0.385$ m, inner diameter $\varnothing_V = 0.1$ m) fitted with a transparent circular tube ($L_D = 1.6$ m, $\varnothing_D = 0.036$ m) by recording the self emitted light. However, this setup does not allow to fully observe the passage of the flame from the vessel to the duct because the metallic flange inserted to connect the chamber to the tube prevents visualization of this zone of propagation. Therefore, a series of experiments was performed in a special setup: a two-dimensional chamber (two parallel glass walls) with a duct leading to the open air. The chamber is 0.1 m in width, 0.385 m in length, and 0.036 m in depth. The duct has the same length (0.385 m) and is 0.036 m x 0.036 m in cross section. The width ratio of chamber to duct is therefore the same than for previous experiments with the cylindrical apparatus. Moreover, the parallel glass windows are suitable for coupling the schlieren technique with high frame rate video recordings. Ignition is achieved by a small electrically heated wire, placed on the axis near the closed end of the vessel, and overpressure variations in the vessel were recorded by a KISTLER piezoelectric gauge mounted at the vessel wall (near the ignition point).

Fig. 1 presents typical sequences of flame passage from the chamber into the duct for a stoichiometric propane air mixture. The process is similar to that described in [1], but displays slight differences. In particular, the secondary explosion is followed by a backward flow of burnt gases into the chamber (see t = 4 ms), but contrarily to the case of the cylindrical setup, these burnt products are immediately carried away into the duct (t = 5.3 ms), and do not accelerate the combustion of trapped unburned gases in the corners of the chamber. This is

confirmed by pressure evolution in the chamber which decreases before the backward flow enters the chamber. Schlieren records of flame transmission had been performed also by Iida et al. [2], but in conditions different from ours (ratio of discharge section to chamber section very small). It is probably the reason why they did not observe a secondary explosion at the entrance of the tube.
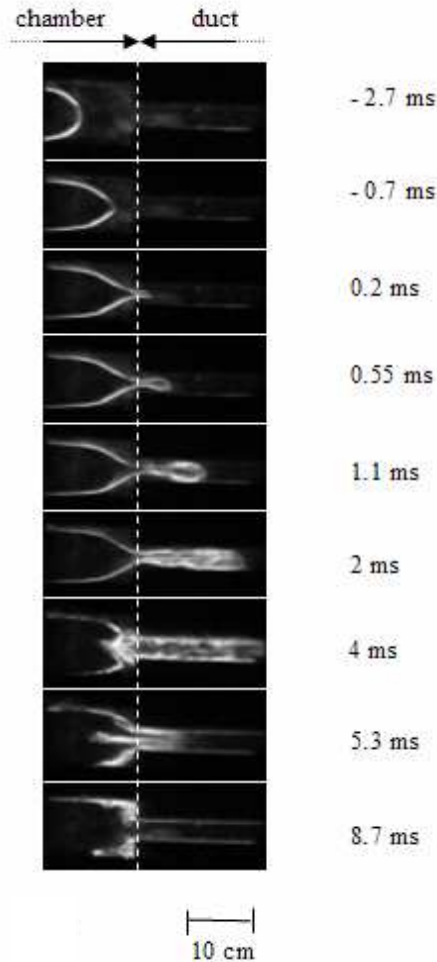

Fig. 1 : Selected frames from schlieren records showing flame transmission from the chamber into the first 20 cm of the duct (t = 0 corresponds to the instant of flame entering the duct).

Besides, this series of photographic records provide more details about the thickness of the flame when entering the duct, and about the velocity profile at the entrance section of the tube. Thus, in the thermal model used to analyze heat transfer to the insert [1], the description of the flow boundary conditions at the upstream side of the insert can be improved.

2.2 Numerical modelling

In order to get more comprehension of the process of flame propagation in the cylindrical vessel and the duct, we have investigated the problem with the help of computational fluid dynamics (CFD) simulations. Similar approach by CFD computations has been undertaken recently by Ferrara et al. [3], to interpret the experimental

results of Ponizy and Leyer [4]. Therefore, we have performed two-dimensional axisymmetric simulations with the FLUENT numerical code. The k-ε model has been used to describe the turbulent flow. The turbulent combustion rate is estimated according to the eddy-dissipation model proposed by Magnussen and Hjertager [5]. The net rate of production of species i, R_i, is given by the smaller of the two expressions below:

$$R_i = \upsilon_i M_i A \rho \frac{\varepsilon}{k} \min_R \left(\frac{Y_R}{\upsilon_R M_R} \right) \tag{1}$$

$$R_i = \upsilon_i M_i AB \rho \frac{\varepsilon}{k} \frac{\sum_P Y_P}{\sum_j^N \upsilon_j M_j} \tag{2}$$

where A and B are empirical constants, υ_i is the stoichiometric coefficient for species i, M_i the molecular weight of species i, N the number of chemical species in the system, Y_P the mass fraction of any product species P, and Y_R the mass fraction of a particular reactant R.

The empirical constant A has been evaluated by matching the calculated time of flame propagation within the vessel with that obtained experimentally for a reference case (large chamber of length $L_V = 0.385$ m and diameter $\emptyset_V = 0.1$ m, connected with the tube of diameter $\emptyset_D = 0.036$ m). All other simulations reported in this work have been obtained by using the same value of A.

However, it can be noticed that when the flame propagates in highly strained regions (especially near the duct entrance), or when the secondary explosion occurs in the duct, the turbulent burning velocity is overestimated by FLUENT, which can cause divergence of the calculations. Consequently, the parameter A needs to be reduced at each time when divergence of calculations is detected.

With these assumptions, the computed pressure history in the vessel matches quite well with the experimental records (see fig. 2).
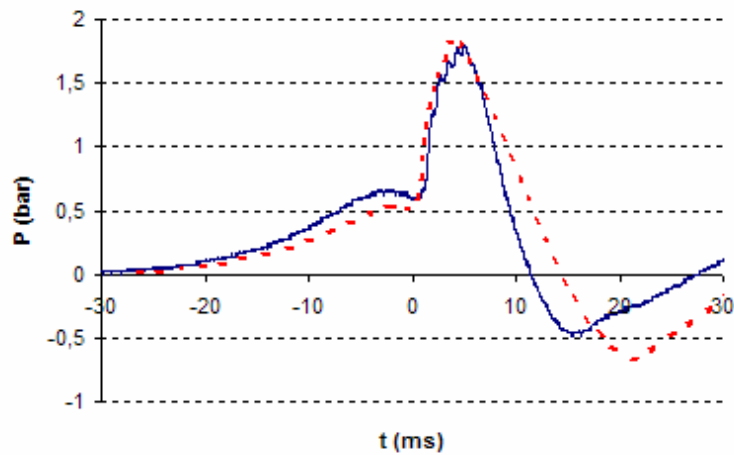

Fig. 2 : Pressure variations in the vessel : experimental – solid line, numerical model – dotted line.
(vessel : $L_V = 0.385$ m, $\emptyset_V = 0.1$ m; duct : $L_D = 1.6$ m, $\emptyset_D = 0.036$m; stoichiometric propane-air mixture; t = 0 corresponds to the instant of flame entering the duct)

An example of comparison between numerical simulations of flame propagation and experimental records is shown in Fig. 3 :
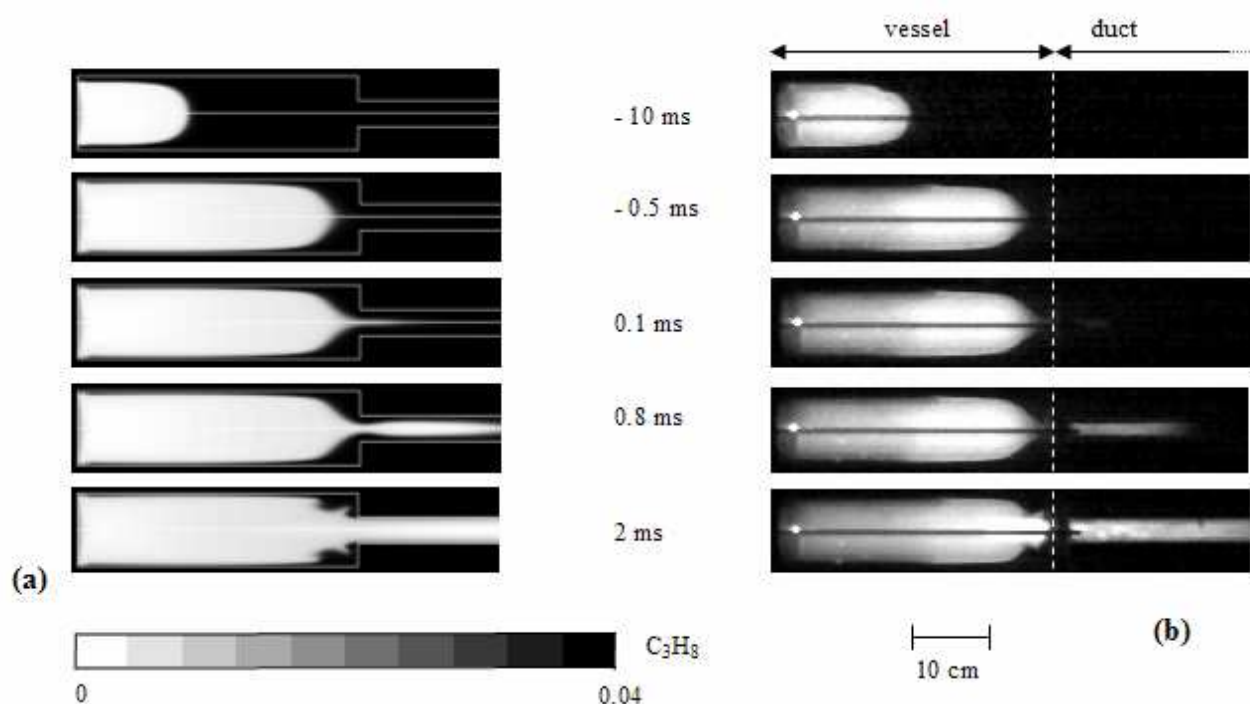

Fig. 3 : Flame propagation in the vessel and along the duct : **(a)** selected displays of computed propane mass fraction; **(b)** frames from camera records at the same instants

The propane mass fraction is plotted in Fig. 3a. The strong gradient of mass fraction between burnt products (level 0 on the grey scale) and cold gases allows us to identify the position of the flame front at different characteristic steps of flame evolution: laminar propagation (t = - 10 ms), front flame stretched at the duct entrance (t = 0.1 ms), secondary explosion (t = 0.8 ms), backward flow of burned gases into the vessel and turbulent combustion of pockets of cold gases in the corners (t = 2 ms). Numerical simulations reproduce quite well the flow dynamics of the whole transmission process.

In previous calculations made with the nodal thermal model for inserts, a constant flow velocity with a uniform gas temperature profile was applied at the duct entrance [1]. Here, the satisfactory agreement between numerical results and experiments justifies using the CFD code to predict the parameters of the flowfield (temperature, velocity) at the duct entrance, in order to precise the boundary conditions assigned in the nodal thermal network model for inserts.

3   Influence of the chamber volume

In many actual industrial conditions, ducts have to be connected to the vent exit in order to prevent the spreading of burnt products in the area surrounding the equipment. Unfortunately, the effect of duct addition has not been enough studied; hence, no reliable method is available to design vent ducts. Several studies on the development of gas explosions in vented vessels connected to a duct have been performed, for example by Ponizy and Leyer [4] and by Molkov [6]. It was seen that the severe increase of pressure in the vessel is triggered by the occurrence of the secondary explosion in the duct.

Here we have investigated the influence of different geometric parameters of the experimental setup on pressure evolution in the chamber and on the process of flame transmission or quenching at the tube entrance. Fig. 4a presents the pressure history for a vessel of reduced length ($L_V = 0.14$ m instead of 0.385 m). The maximum pressure reached in the chamber is decreased, in accordance with the decrease of the ratio V/S of chamber volume to discharge surface (from V/S $\approx$ 300 to V/S $\approx$ 100), which is in agreement with existing results on vessel venting [7].

For this vessel with reduced length, when diminishing the tube diameter down to 0.021 mm so that to maintain the V/S ratio equal to 300 (Fig. 4b), CFD numerical simulations as well as experiments indicate that pressure evolution in the small chamber is similar to that observed in the longer chamber (0.385 m) with a tube of larger diameter (0.036 m): the maximum pressure reached is about 2 bars, which is close to the value obtained in the reference case (1.8 bars, see Fig. 2).
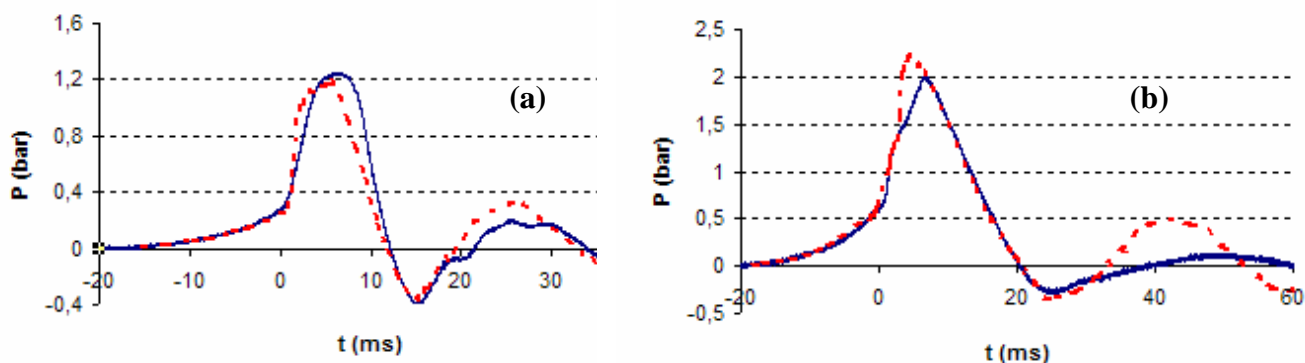

Fig. 4 : Experimental (solid line) and calculated (dotted line) pressure evolution in the vessel of length 0.14 m : **(a)** with tube diameter 0.036 m, (V/S $\approx$ 100) ; **(b)** with tube diameter 0.021 m, (V/S $\approx$ 300).

For these new geometrical conditions (chamber $L_V = 0.14$ m equipped with the discharge duct of diameter $\emptyset_D = 0.021$m), we have calculated with our nodal thermal model the insert characteristics which would be required to quench the flame at the tube entrance. In previous works [1], we have shown that the process of the flame transmission within the insert is strongly related to its geometric characteristics, mainly compactness and length. Flame quenching may be achieved via different arrays of these parameters. For example, in an insert with a given number of rolls, the flame may be totally quenched when the wire net is sufficiently long. In the same insert but with a shorter length, the flame is partially quenched (the flame is stopped in the insert and then emerges, preventing the occurrence of a secondary explosion). Under a critical value of the insert length, the flame is no more quenched: the secondary explosion is just delayed and occurs later in the tube.

In the present work, we have first calculated, with the nodal thermal model, the insert length which would be theoretically required to quench totally the flame at the tube entrance. Then, experiments were performed with inserts having the same number of rolls and of variable lengths. The length was diminished progressively to obtain the different processes of flame transmission. Predictions given by the calculations lead to results in good agreement with experiments.

Thus, our model seems to be an interesting tool to investigate conditions of flame quenching at different scales and could be useful to design concrete devices for quenching flames in industrial conditions.

References

[1] Henneton N, Ponizy B, Veyssière B (2006). Control of flame transmission from a vessel to a discharge duct. Combustion Science and Technology. 178: 1803

[2] Iida N, Kawaguchi O, Sato GT (1985). Premixed flame propagating into a narrow channel at a high speed. Combust. Flame. 60: 245

[3] Ferrara G, Di Benedetto A, Salzano E, Russo G (2006). CFD analysis of gas explosions vented through relief pipes. Journal of Hazardous Materials. 137: 654

[4] Ponizy B, Leyer JC (1999). Flame dynamics in a vented vessel connected to a duct. Combust. Flame. 116: 259

[5] Magnussen BF, Hjertager BH (1976). On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion. In : Proceedings from the 16th Int. Comb. Symp. (pp. 719-729)

[6] Molkov VV (1994). Venting of deflagrations: dynamics of the process in systems with a duct and receiver. In: Proceedings of the Fourth Int. Symp. on Fire Safety Science, Canada (pp. 1245-1254)

[7] Siwek R (1998). New findings on explosion venting. In: Paper to the Loss Prevention Symposium, Barcelona